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Final Report for

FEASIBILITY OF TECHNIQUES FOR MONITORING PHYSIOLOGICAL VARIABLES WITHOUT ATTACHED SENSORS

Contract NAS12-1

4 November 1966

Prepared by

Life Sciences Operations

NORTH AMERICAN AVIATION, INC.
SPACE and INFORMATION SYSTEMS DIVISION

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FOREWORD

This final report on the study of the Feasibility of Techniques for Monitoring Physiological Variables Without Attached Sensors was prepared by Life Sciences Operations for the Electronic Research Center, Cambridge, Massachusetts, under contractual requirement NAS12-1.

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ABSTRACT

A SURVEY OF REMOTE OR UNATTACHED SENSORS THAT MIGHT BE APPLIED TO PHYSIOLOGICAL MONITORING DEMONSTRATES CAPABILITY FOR REMOTE MEASUREMENT OF EYEBLINK, EYE MOVEMENT, AND PUPILLARY DIAMETER. REFINEMENT OF THE NECESSARY INSTRUMENTATION, SIGNAL CONDITIONING EQUIPMENT, AND DATA ANALYSIS EQUIPMENT APPEARS WITHIN THE CAPABILITY OF PRESENT TECHNOLOGY. PROGRAMS ARE RECOMMENDED TO OBTAIN CORRELATIONS OF THE PARAMETERS OF EYEBLINK, EYE MOVEMENT, AND PUPIL DIAMETER WITH THE CLASSICAL EEG AROUSAL STATE AND MENTAL TASKS.

CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

Whenever humans are placed in hazardous or unknown environments for research purposes, it has become common practice to monitor some physiological parameters as a safety index. One or many aspects of the physical environment also have been monitored. In general, physiological parameters chosen for surveillance have been derived from the vital signs of the clinician—temperature, pulse, and respiration. Pulse-rate measurements have been expanded, where possible, to blood pressure and the electrocardiogram. In addition to respiration rate, it may be highly desirable to know tidal and minute respiratory volumes or even oxygen consumption or carbon-dioxide production or both.

Historically, medical monitoring of experimental subjects, or humans in operational conditions such as space flight, has had as its sole purpose the health and safety of the human involved. In future space flights, the scientific aspects of each mission will increase in number and sophistication. Hence, an important contribution of future monitoring systems will be the assurance that data collected will be valid; i. e., the crewman responsible for a given datum was in good health, in full possession of his senses, and, hence, capable of making the required measurement. A second facet of this problem lies within the area of assuring the psychological condition of the crewman; this area is beyond the scope of the present discussion.

Physiological monitoring systems developed to date have been basically modifications of clinical instruments. Signals from the electrodes or sensors are much like those obtained clinically and, hence, have a broad background of research and experience upon which interpretations can be based.

Current techniques utilize electrodes and sensors attached to the body. No serious problems arise for short-term, well-controlled situations, but prolonged experiments or studies in operational environments give rise to two problems: (1) changes in electrode characteristics with time can, and in some cases do, alter the accuracy of measurements, and (2) the electrode harness and its connections restrict and, to some degree, restrain the subject. Some scientists consider that the attachment of a monitoring system in itself represents a significant stress to the subject.

Monitoring signals are usually transmitted on wire, even though miniaturized telemetry equipment is available, with the subject or crewman "connected" to his vehicle. A recent incident shows some problems to be expected in such cases. Several competition sports car drivers were instrumented during the Daytona Continental race. An instrumented driver spun out and attempted to push his car off the track to avoid being hit by others. The umbilical connecting him to the recording equipment in the car so restricted his movements that he grabbed the wire with both hands and tore the umbilical away. He then cleared his car from the track.

Clearly, sensor connections impair freedom of motion and, in emergencies, may impede reactions. The results could be disastrous. The need for remote monitoring equipment is therefore logical and obvious. Since little or no effort has been placed in this direction, there is a paucity of data and even a lack of fundamental approaches to remote monitoring.

This study is primarily a survey of existing literature pertinent to the monitoring of human physiological functions, with recommendations for further research and development. In addition, some preliminary data were gathered from existing equipment to determine laboratory feasibility of remote monitoring. It was decided to study in more detail the relationship between eyeblink and eye movement as they might reflect human arousal states.

STUDY OBJECTIVE

The primary objective of this study was to survey remote or unattached sensors that might be applied to physiological monitoring. It was obvious from the beginning that some section of the electromagnetic spectrum would be involved in most cases. Therefore, a survey of physiological variables that had or could be detected by electromagnetic radiation on an active or passive basis was conducted. A survey of literature on biomedical instrumentation with respect to remote or unattached sensors was also performed.

Not all attention was focused on the electromagnetic spectrum. The possibility of detecting body effluents (expired gases, flatus, etc.) was considered. However, as distance from the body increases, detection, diffusion, and other physical processes reduce measurement accuracy to the point of uselessness.

The general constraints adopted, as follows, were based on requirements of the study and consideration of a possible mission in which such a system might be used:

1. The sensor should not touch or be attached to the subject's body or restrain him in any manner.

2. The sensor and associated electronics should be capable of adaptation to flight-qualified hardware.

3. Since the type of mission on which such a system would be used will be of long duration (e.g., Mars/Venus flyby), it is assumed that a shirt-sleeve environment will exist; use of the pressure suit as part of the measurement system will not be considered.

4. Instrumentation of garments, individual couches, etc., although feasible, was not considered to any great extent in the course of this study.

5. It is assumed that, at some point in the daily activity routine, the crewman would be required to position himself at a predetermined point for "viewing" by the remote system. This positioning might be at a control panel while performing other tasks or in his couch just before or after a sleep cycle.

6. Biochemical monitoring of body fluids was not considered.

PHYSIOLOGICAL MONITORING IN SPACE

Since the intent of this program was to determine the feasibility of remote monitoring for long-duration space missions, it is necessary to consider several constraints that under many other conditions would not be constraints:

1. Need for monitoring projected to future time and future missions

2. Physical dimensions: weight, power, and volume

3. Time required by each crewman to perform measurements

4. Data format, storage, and transmission

5. Mission model: duration, crew size, and orbital or interplanetary

6. Relationship to other experimental programs

These constraints are mission specific and cannot be considered in detail at this time, but several pertinent statements may be made and have served as general ground rules during this study. In practice, as an originally unknown environment becomes better studied and understood, the hazard or risk to persons in that environment can be evaluated more intelligently. Requirements for intensive monitoring may be reduced or deleted or, as an alternative, emphasis may be shifted from short-term to long-term effects. It is predicted that space missions of the 1970's and 1980's will carry less physiological monitoring equipment as we now know it. In general, it can be reasoned that the emphasis will shift to monitoring long-term effects of space flight and, in particular, performance ability on a predictive basis. Recent studies such as Lunar Exploration Systems for Apollo (LESA) (Reference 1) have indicated that the major responsibility of the biomedical community will be to predict the ability of a crewman to perform intricate scientific measurements and observations in other disciplines.

Studies related to extended operations in earth orbit (BAHFR, AAP, etc.) (References 2 and 3) have pointed up a serious problem in physiological monitoring. Using currently accepted techniques, a system considered to give the minimum safety information would require 140 minutes per man per day (Reference 2). Estimates vary from study to study but, when added to station-keeping time, personal hygiene, eating, and sleeping, little time is left for scientific experiments.

The time required for biomedical monitoring of a crewman, using present techniques, is largely a function of the time required for attaching electrodes and/or transducers. The attachment is accomplished by a second crewman, and his time is also expended. Unattached sensors would eliminate the attachment time for both men and reduce total time requirements to measurement time alone.

CRITERIA FOR PHYSIOLOGICAL MONITORING

As already mentioned, physiological monitoring variables have been selected on the basis of clinical significance. In short-term, low-hazard situations, they may be as simple as the vital signs of temperature, pulse, and respiration. In long-duration, high-hazard environments, the list may be extensive and include some environmental parameters.

In a recent study (Reference 2) of biomedical instrumentation for earth-orbital vehicles, the requirements for a minimum safety package were derived (Table 1). The criteria used for this study may be used here with some modification. Initially, one must assume that the primary space hazard will be weightlessness. Thus, the changes in physiological systems induced by prolonged exposure to the weightless environment should be given greatest attention by the medical monitor.

The cardiovascular system has been considered to be the physiological system most susceptible to weightlessness. To monitor this system ideally, one would like to have a measurement of the cardiac output. This measurement is difficult, however, and is of some risk to the subject. It has become necessary to use blood pressure and the ECG as acceptable substitutes in

Table 1. Safety Package

Identification	Measurement	Device	Weight	Power (watts)	Item	Margin		Workspace	Frequency (No. /Wk)	Duration		Time/Week		Total Cumulative
			Item			Storage	Spare			Subject	Observer	Subject	Observer	Cumulative Minimum/Week
					Volume (cubic feet)									
15	Blood pressure	B	1.25	0	0.049	0.067	0.067	(O_{s-1}, S_{s-2})71.0	14	5	5	70	70	140
35	Cardiac activity and state (Electrocardiogram)	C	0.125	0.02	0.0005	0.006	0.0012		14	10	15	140	210	490
143	Venous distention	Checklist	-	-	-	-	-	(O_{s-2})330	14	5	5	70	70	630
63	Pulse rate	Stopwatch	0.022		0.0003	0.001	0.006		7	2	2	14	14	658
125	Food intake (eating habits evaluation)	Checklist	-	-	-	-	-		7	0	0	0	0	
89	Bowel habits (function evaluation and stool)	Checklist	-	-	-	-	-		7	0	0	0	0	
135	Regurgitation and nausea	Checklist	-	-	-	-	-		7	0	0	0	0	
13	Fluid intake and output	Checklist	-	-	-	-	-		7	0	0	0	0	
21	Urinalysis (WBC, RBC, pH, sugar, bacteria, protein, osmolarity)	KQ, R	75.9	175	1.98	2.47	2.60		7/3	0	5	0	12	670
27	Hematocrit and hemoglobin	A, A, E, F, G	16.5	75.0	2.55	3.187	3.250	(O_{s-1})38.0	7/3	5	25	12	55	737
99	Respiratory rate	C	-	-	-	-	-		14	(See No. 35)	0	0	0	
78	Body temperature	U	0.06	-	0.0012	0.0015	0.0005		7	5	0	35	0	772
95	Muscle size	O	0.125	-	0.0012	0.0015	0.0030	(O_{s-1}, S_{s-2})66.0	7/3	5	5	12	12	796
1	Arm-hand manipulation	A, B	1.25	-	0.039	0.049	0.049		7/3	10	15	25	35	856
10	Speech perception	G, H	22.5	2.0	1.03	1.287	1.662		7/3	10	0	21	0	877
3	Computation	B, C, D	0.3	0.2	0.014	0.017	0.049		7/3	20	0	48	0	925
98	Cardiopulmonary symptoms (Dypsnea)	Checklist	- -	- -	- -	- -	- -		7 -	0 0	0 0	0 0	0 0	
101	Voiding evaluation	Checklist	0.2	0	0.001	0.001	0.001		7	2	5	14	305	974
	Total safety package		117.1 total	11.0 Maximum			7.690 total	208 total	Min/man/wk			461	513	974
									Min/man/day			65.9	73.3	139.2
									Hr/man/day			1.09	1.22	2.32

Work space Legend

O_{s-1} - Observer, or S_{s-1} - Subject (standing) - 38 cubic feet
O_{s-2} - Observer, or S_{s-2} - Subject (seated) - 33 cubic feet
S_a - Subject seated in accelerator device - 90 cubic feet

physiological monitoring. Similar reasoning could be applied throughout the physiological systems, but this would only serve to belabor the point.

With the environment and its potential physiological effects in mind, one may select a set of variables by which he might monitor the crewman's health and safety. The criteria applied to the selection of the monitoring instrumentation are:

1. Feasibility of measurement under weightless conditions, including constraints placed on the monitoring system by the space vehicle and its mission

2. Ability of the measure to detect effects of weightlessness

3. Clinical validity of the measure

4. Availability of instrumentation or the potential for hardware development

Having applied the above measurement criteria, this set of evaluation criteria should be applied:

1. Validity—the degree to which the datum obtained reflects the measure desired

2. Sensitivity—the degree to which the particular measure can detect small changes

3. Predicability—the degree to which a measure can indicate future biomedical status of a given individual

4. Crew status—the degree to which a given measure indicates the health and safety of a crewman

These criteria were applied to the measures and techniques considered in this study and to an additional criterion: Is there a physical method, theory, or concept that could make this measurement without attaching sensors to the body?

SURVEY OF THE LITERATURE

The first step in establishing design criteria for a remote monitoring system is to examine the secondary physiological events related to the parameters of interest and to determine their applicability for remote detection. The basis of such an approach lies in the concept that secondary physiological events are part of an overall system regulated by a complex control mechanism. The purpose of the control mechanism is to maintain the integrity of the individual in a dynamic external environment. Changes in a given subsystem imposed by some functional demand are not singular but manifold. Thus, physical changes at a secondary level depend directly on the primary change.

An example of such primary and secondary relationships can be illustrated in the cardiovascular system. The primary cardiovascular response to an increased muscle work output by the heart is an increased blood flow to the working muscles. This increased flow results from a faster heart rate and a slight increase in stroke volume and pulse pressure. At the secondary level, ideal unattached sensors would detect increased distension of arteries near the surface, increased mass in the muscles because of the increase of blood volume at that point, increased surface temperature, etc. Some of these secondary events can be monitored by a proximity detector (Reference 4) that can be useful in detecting surface displacements. Since the absorbance of light by hemoglobin near the surface of the skin has been noted to pulsate with blood flow, and the absorption spectra of hemoglobin depend on the ratio of oxyhemoglobin to total hemoglobin, each heart beat can be detected by reflection photometers based on the ear oximeter principle (Reference 5). Furthermore, it may be possible to detect blood-volume flow by changes in the transmission of electromagnetic or ultrasonic waves through the body.

Windsor and Bendezu (Reference 6) have recently demonstrated the ability of infrared thermography to detect changes in peripheral blood flow in some clinical situations. It would seem that this technique might be modified as a remote sensing device.

It should be pointed out that the application of a remote monitoring system will have to deal with men in a shirt-sleeve environment as well as in pressure suits. For purposes of this program, emphasis was placed on the shirt-sleeve condition.

Except for infrared thermometry, environmental parameters will not be considered in this discussion, even though it is realized that parameters such as total pressure, oxygen partial pressure, temperature, and humidity can be valuable secondary monitoring parameters. They could also serve as a background for interpretation of data received from the physiological monitoring system.

CHARACTERISTICS OF AN UNATTACHED SENSOR SYSTEM

Even though physiological monitoring without attached sensors is uniquely complex and difficult, it can be considered as a system composed of transducers, amplifiers, and recorders. The correct selection of the transducer is essential to system success. Making this choice hinges, in turn, on a thorough understanding of underlying physiological processes. The performance requirement for a monitoring system using unattached sensors (or for any monitoring system) can be set down as follows:

1. Static Accuracy—The ability to record stationary or slowly varying events requires two qualities: stability and uniqueness. The first requires freedom from a drifting base line (point of reference) and from a drifting calibration or gain factor. The second necessitates unique response to a static signal no matter how it is applied.

2. Dynamic Accuracy—The fidelity of the system's response in simulating the dynamic event is also affected by two variables. The first is system noise level, the component of the output signal originating outside the test event; both electrical and mechanical noise are sources of error. The second determinant of dynamic accuracy is dynamic response, or the system's ability to follow rapidly changing phenomena with uniform amplitude response and negligible phase-lag.

3. Physiologic Reactance—This is the effect (normally undesirable) that the monitoring system has on the event being monitored. Of particular importance is the degree to which the sensor alters the structure or the functioning of the subject and the consequent signal error.

The transducers, as used in monitoring work, sense secondary physiological events and use a small amount of energy from the event to control a larger energy output from amplifiers. As long as the energy extracted from, or added to, the parameter being sensed is less than some arbitrary value established as the point at which it would alter the significance of the phenomenon being monitored, the sample is considered to be a true indication of the monitored event.

SECONDARY PHYSIOLOGICAL EVENTS

The significant secondary physiological events that manifest themselves in a form that can be detected without direct contact can be categorized in 12 areas:

1. Mass Acceleration—Characterized by body motion, respiration, and cardiac activity.

2. Surface Motion—Characterized by the emotional state of the subject; surface motion can be described as sliding of skin without marked shift in body mass such as eyeblink, pupil dilation, lip curl, swallowing as indicated by motion of the larynx, or other motions parallel to the surface of the body.

3. Volume Displacement—Characterized by breathing, contraction of the heart, and body motion, which have components primarily normal to the body surface and are at a constant velocity (in order to differentiate from mass acceleration).

4. Effluents—Characterized by body production of carbon dioxide, flatus, and sweat.

5. Sounds—Characterized by emission of breathing noises, heart sounds, and bruxing.

6. Acoustic Impedance—Characterized by calcification within the body and blood-volume flow.

7. Surface Hardness and Texture—Characterized by surface temperature and peripheral blood-volume flow.

8. Electromagnetic Reflection—Characterized by blood-volume flow and hemoglobin content.

9. Electromagnetic Transmission—Characterized by respiration, blood-volume flow, and gross body motion.

10. Electromagnetic Radiation—Characterized by surface temperature and magnetocardiogram peripheral blood flow.

11. Electromagnetic Absorption and Reradiation—Characterized by absorption of heat and transport of heat by blood-volume flow.

12. Electrostatic Charge Distribution—Characterized by current depolarization pathways of the heart.

LITERATURE SURVEY FOR UNATTACHED SENSORS

An investigation of literature on unattached sensors indicates that infrared devices, doppler sonar systems, electric field detectors, photoconductive cells, proximity devices, accelerometers, video differential planimeters, and magnetocardiographs have been used and tested as unattached sensors. Some techniques show more promise than others with respect to static and dynamic accuracy, sensitivity, reliability, physiologic reactance, and ability to detect events at a reasonable distance. A brief discussion of these sensors follows.

Infrared Devices

Modern infrared detectors, notably the cooled photoconductive devices developed for military purposes, have made it possible to produce a heat picture composed of some 40,000 bits of temperature information from an area as large as the chest wall in 30 seconds (References 7, 8).

Although there is no fixed value for skin temperature in a normal individual under standard environmental conditions, there is a temperature symmetry; that is, an area of skin on one side of the body is at the same temperature as its mirror image on the opposite side. Thus, thermography can be demonstrated in a simple manner; departures from this symmetry, even though these departures are no more than one or two degrees centigrade, indicate abnormal conditions.

Local increases in temperature, or hot spots, can occur over regions of inflammation or abscesses, or in other conditions where local metabolism is increased. Cold spots, or areas where temperature is diminished, can occur over collections of inert fluid (cysts), over fatty tissue, and over dead, dying, or blood-deprived tissue. Temperature patterns normally reflect the fat distribution and blood supply of the tissue, and this often remains remarkably constant in a healthy person.

Changes in blood supply will alter the thermograph. Increased blood flow, either by dilation of vessels or by abnormal connections between arteries and veins, will increase skin temperature. Diminution of blood supply, through blocks or narrowing of arteries, will cause cold areas; likewise, increased heat conduction from the warmer body core to the surface, which may occur following injury, will give rise to hot spots.

Doppler-Sonar Systems

A doppler-sonar system can be used for monitoring surface displacements. A system with a 455-kc source has been used for monitoring gross body movements without contact in the air (Reference 9). Experiments that sensed heart beat and throat motion during speech have been performed. In conversations with the president of a company (Janus Products, 210 Michael Drive, Syosset, N.Y.) supplying doppler-sonar equipment, developmental models of devices having phase detectors sensitive to body motions of as little as 0.0001 inch were reported to be feasible.

Electric Field Detectors

The body is a conductor that can distort an electrical field. Consequently, volume displacement or body motion in the neighborhood of an electrical field will distort that field. This distortion can be sensed by pickup coils and amplified to indicate blood flow, respiration, and gross body motion. Schafer (Reference 10) has demonstrated this theory recently by monitoring the field distortion caused by volume displacement. However, its relationship to physiological events has yet to be established.

Photoelectric Cell

A simple, dependable method has been demonstrated by J. Weinman et al. (Reference 11) for indirectly measuring blood pressure in experimental animals. This technique employs a sensitive photoconductor cell measuring reflected light for the study of peripheral blood circulation. The sensor is small, and its sensitivity in the red part of the light spectrum is high. By utilizing these properties, it was possible to develop a simple and efficient technique for indirect blood-pressure measurements and pulse-rate counting. Additional work using scattered light has been done (Reference 5).

Proximity Devices

A thorax placed in an electric field will cause distortion, because the thorax is a conductor. This distortion affects the value of the electrical capacitance between two probes placed in the electrical field but not in contact with the thorax. As the thorax changes its geometry due to respiration and atrial or ventricular contraction, the capacitance between the probes will vary. In addition, the blood-volume distribution with time affects the electric field. A capacitance sensor based on the above concept has been developed (References 12, 13, 14). This unattached sensor has an unusually good frequency response, compared to unattached sound sensors, because it does not employ the air transmission of sound with the resultant losses in the impedance mismatch between the high density of the chest wall and air.

If one probe is attached to the thorax, the capacitance sensor approximates a proximity device. With this configuration, several experiments were performed using a commercial proximity device, including amplifiers, filters, and recorders. Preliminary results indicate that the changes in electrical capacitance between the thorax and unattached probes contain respiration, heart rate, and blood-volume data (Appendix A).

Accelerometers

The ballistocardiogram is a near-classic example of the use of indirect sensors. It has reached its ultimate in the weightlessness experiments of the U.S. Navy (Reference 15), where a KC-135 jet transport was flown in a parabolic profile while a subject on an instrumented litter was monitored for linear and rotational acceleration.

In contrast, E. Willbarger (Reference 16) has developed a laboratory device utilizing the principle of the ballistocardiograph to determine heart rate without direct contact. This device consists of a chair with a vibrationally isolated seat on which a highly sensitive piezoelectric accelerometer is mounted. When a subject is seated in the chair, the forces exerted by the pumping action of his heart are sensed and transduced.

Video-Differential Planimeters

The video-differential planimeter is an instrument that measures variations in the projected area of any remote object with the aid of a flying-spot scanner or television camera system. The composite video signal, caused by the scanning of the object and its contrasting background, is shaped to yield a sequence of constant-amplitude rectangular pulses that are negative-going during a scan of the object and positive-going at all other times. If the subject's projected area varies, the readout voltage will vary proportionately. This technique has been shown by Tobin (Reference 17) to be capable of measuring respiration rate and heart rate.

Magnetocardiographs

Experiments conducted by Stratbucker (Reference 18) on isolated hearts have revealed the existence of a detectable magnetic field associated with cardiac electrical activity. The relationship between the magnetic record and the ECG has been explored, and it has been shown that the voltage induced in the sensing coil has the form of the first derivative of the ECG. Other experimenters (Reference 19) have measured the magnetic field external to the body with similar results. This technique is extremely sensitive to the motion of the sensor in the earth's magnetic field and to placement with respect to the subject's heart. From the data in the above references, calculations indicate that the sensing coil would be large and have an excessive weight and volume.

SENSORS NOT DESCRIBED IN THE LITERATURE

Sensors that have not been fully studied but that show promise as unattached sensors are parabolic microphones, CO_2 samplers, and optical techniques. Parabolic microphones can be mounted so that a small surface area on the body can be observed. In this manner, it may be possible to monitor respiration sounds, and possibly even pulse rate, from heart sounds superimposed on the respiration sounds.

CO_2 samplers can be used to monitor respiration rate; experiments in the laboratory, however, have shown that a rather restricting effluent-collecting duct is required along with high air velocities if the continuous respiration rate is to be sampled. An external IR beam crossing in front of the face has been considered.

Optical techniques can be used as unattached sensors by monitoring surface motion such as eyeblink and swallowing. This procedure would radiate a light beam (possibly an IR beam), and changes in the beam reflection would indicate surface motion.

Experiments with balanced photodetectors have shown that a reliable respiration pattern can be sensed when the detectors are used to sense the edge of the subject's thorax against a contrasting background.

Other experiments with opthalmoscopes have shown that coaxial corneal reflections are a reliable method of monitoring iris dilation and eyeblink. This technique is fairly insensitive to head rotation, and a simple servo system can be made to follow the cornea.

COMPARISON OF SENSORS WITH SECONDARY EVENTS

The secondary physiological events and their respective unattached sensors are shown in Table 2.

PHYSIOLOGICAL MEASUREMENTS

The significant physiological measurements that can be monitored indirectly by their associated secondary physiological events are pulse rate, respiration rate/volume, surface temperature, blood pressure, blood-volume flow, blood velocity, red blood cell count, blood pulse-wave velocity, plethysmogram, ballistocardiogram, electrocardiogram, phonocardiogram, vibrocardiogram, work output of the heart, electroencephalogram, and gross body motion. Many of these measurements involve the same basic physiological parameters but, for completeness, all significant physiological measurements are listed and discussed in the following paragraphs.

Table 2. Unattached Sensors for Secondary Physiological Events

Secondary Physiological Events	Unattached Sensors
Volume displacement	Video-differential planimeters, proximity devices
EM transmission	Electric field detectors, photodetectors
Mass acceleration	Accelerometers
EM radiation	Infrared devices, magneto-cardiograph
EM absorption and reradiation	Infrared devices, photoflash, and diathermy
Surface motion	Optical techniques
EM reflection	Photodetectors, electric field detectors
Sounds	Parabolic microphone
Electrostatic charge distribution	Electric field detectors
Surface hardness and texture	Optical techniques, doppler-sonar systems
Effluents	CO_2 sampler
Acoustic impedance and reflectance	Doppler-sonar systems

Pulse Rate

Energy consumption of the human body can be determined by analogy from the pulse rate (Reference 20). Furthermore, the work output of the heart can be estimated from the pulse rate if the storke volume and ventricular pressure are known. Light or sedentary work requires 70 to 80 beats per minute, moderately heavy work 80 to 100, and very heavy work 100 to 130. Existing unattached sensors that can be used for monitoring pulse rate are doppler-sonar systems, electric field detectors, photodetecting cells, proximity devices, accelerometers, video-differential planimeters, and magnetocardiographs. It may also be possible to use sensitive directional microphones.

Respiration

Respiratory measurements are useful in determining the amount of oxygen consumed by a subject and any changes in the rate and depth of respiration. Furthermore, the level of metabolic activity can be estimated by respiratory frequency (Reference 21). Existing unattached sensors that can be used for monitoring respiration are doppler-sonar systems, electric field detectors, proximity devices, and video-differential planimeters. It may be possible to use direction-sensitive microphones or IR detectors that measure the absorption of IR radiation by CO_2 and moisture in the exhaled breath.

Temperature

Under steady-state conditions, heat flows at uniform rates from the sites of production in the body to cooler tissues or blood. The blood carries the heat to the body surface, where it is dissipated to the external environment by radiation, convection, and evaporation. Temperature gradients between regions of the body core and skin surface thus remain somewhat fixed. Increased heat production during work results in transient changes in these gradients, thus leading to the thermoregulatory responses that establish a new body temperature equilibrium at a higher level. In addition, the temperature gradients are altered by the autonomic regulatory function that can reflect the emotional state of the subject. Existing unattached sensors that can be used for monitoring temperature are infrared devices (Reference 7) that measure the electromagnetic radiation emanating from the body surface. Alternately, they can measure the absorption or transporting of heat through the body from external sources, such as pulses of electromagnetic energy on localized areas.

Blood-Volume Flow

Measurement of blood-volume flow is important in determining circulatory problems and in detecting changes in the internal resistance of blood vessels. Furthermore, changes in an individual's emotional state are reflected in, or accompanied by, changes in autonomic functions (Reference 22). In order to detect these autonomic alterations, measurements of the change of activity in various organs and organ systems must be made. One such organ system is the peripheral blood-flow process. It is directly and indirectly influenced by the autonomic nervous system. The measurement of blood-volume flow also gives by analogy blood pressure, blood velocity, and blood pulse-wave velocity if the proper correlations can be found.

Existing unattached sensors that can be used for monitoring blood volume flow are infrared devices, electric field detectors, photodetector cells, and proximity devices.

Red Blood Cell Count

Measurement of the red blood cell count is important in determining the degree of blood damage due to ionization radiation and in estimating the general health of the subject. It may be possible to infer this physiological indicator indirectly by monitoring the absorption spectra of hemoglobin, oxyhemoglobin, and their ratio.

Plethysmographs

Plethysmographs measure the change in tissue volume resulting from an increase in the quantity of blood that the tissues contain. Rhythmic fluctuations of blood content cause the body tissue to expand or contract during the cardiac cycle, with a consequent change in tissue electrical or acoustical impedance. Existing unattached sensors that can be used for estimating the plethysmogram are infrared devices, electric field detectors, photodetecting cells, and video-differential planimeters.

Ballistocardiographs

A ballistocardiograph (BCG) detects and measures the small movements produced in the human body under the influence of the displacements of heart and blood that occur in connection with cardiac activity. Accelerometers have served as useful unattached sensors to measure the BCG when embedded in the subject's chair, cot, etc. Analysis of BCG produces pulse rate and gives by analogy an indication of blood pressure, blood flow, and work output of the heart.

Phonocardiographs

Phonocardiographic equipment provides continuous, instantaneous recording of beat-to-beat changes in heart rate, as well as noises due to acceleration of the blood mass within the heart. An unattached version of a phonocardiograph would consist of a sensitive, directional microphone. The feasibilities of such a system, however, have not been fully explored at this time.

Electrocardiographs

An electrocardiograph (ECG or EKG) detects and measures electrical potentials generated in conjunction with the contraction and relaxation of the heart muscle. Waveforms and amplitudes have been correlated with heart action. Thus, abnormalities show up as variants from empirically established norms. An adjunct to the conventional ECG is the vector ECG. Since the electrical potential on the surface of the torso can be explained approximately by the motion in time of a current dipole within the heart, the dipole can be represented as a time-varying vector. Visualization of the three vector components is possible using a cathode ray tube (CRT) display. The CRT can display the horizontal, frontal, and sagittal projections of the current dipole vector that represents the vector ECG by unattached sensors. The first employs external voltage pickup coils to detect the electromagnetic field from the current dipole (Reference 19). It has been shown that the sensed voltages are related to the derivative of the ECG (Reference 18). They are extremely weak, however, even when measured close to the body, and are consequently subject to an unfavorable signal-to-noise ratio. The second method measures the electrostatic field resulting from surface-charge density on the torso. The surface-charge density is due to the current dipole in the torso. This technique has not yet been fully explored.

Vibrocardiographs

A vibrocardiograph (VCG) detects and measures the small vibrations in the chest wall associated with heart contractions and expansions. A proximity detector can be used as an unattached sensor to monitor the small movements of the chest wall. Doppler-sonar systems can also be used.

Work Output of the Heart

The work output of the heart consists of the amount of energy it transfers to the blood while pumping it into the arteries. Energy is transferred to the blood in two forms: (1) by far the major proportion is used to move the blood from the low-pressure veins to the high-pressure arteries; (2) a minor proportion of the energy is used to accelerate the blood to ejection velocity for passage through the aortic and pulmonary valves. Unattached sensors for this task would determine the heart rate, ventricular blood-volume flow and stroke volume, and then, by analogy with blood pressure, an estimate of the work output.

Electroencephalography

An electroencephalograph (EEG) detects the rhythmically varying potentials produced by the brain, using multiple pairs of electrodes in various positions on the scalp. By examining the potentials, it is possible to diagnose a variety of neurological disorders and to measure the state of consciousness of an individual. Unattached sensors that may give by analogy the central nervous system arousal level are based on two techniques.

The first echnique is the measurement of eye motion. Pupillary reactions are indicators of automatic nervous activity (Reference 23). Devices that rapidly and continually measure the pupil diameter change in response to given spectral stimuli of known test control have been considered (but not fully examined). An infrared illumination and scanning system is used to measure and record pupil dilation and contraction. The infrared beam, a rapidly moving pinpoint of light, scans the eye in a way similar to that in which a television tube projects an image. The beam's small size and great velocity eliminate the danger of injury to eye tissue.

The second technique is the measurement of surface motions such as eyeblink, lip curl, and swallowing. Here, optical techniques detecting the reflection of the cornea or sclera or proximity devices may be employed as unattached sensors.

Gross Body Motion

The measurement of gross body motion is important in estimating the emotional state of the subject as well as the degree of central nervous system arousal. Existing unattached sensors that can be used for monitoring gross body motions are doppler-sonar systems, electric field detectors, photo-detecting cells, proximity devices, accelerometers, and video-differential planimeters. It may also be possible to use directional microphones and optical techniques.

These, then, were the initial parameters and techniques considered for monitoring; a final selection was based on considerations presented in a later section.

SUMMARY OF LITERATURE SURVEY

Based on the literature available, the constraints of space operations, and the requirements for sensitivity, accuracy, and reliability, seven physiological parameters appear to be accessible by remote monitoring.

Volume displacement of the thoracic cavity, as measured by capacitance distance meters (Appendix A), appears to give a measure of heart action and respiratory patterns. Also, the acceleration imparted to the human body by pulsitile heart action can yield ballistocardiographic data. This system would require instrumentation of the couch.

Infrared detection of body surface temperature as radiation has already found some clinical uses and could well be applied to spacecraft use as a remote monitor. Absorption of infrared energy by the body surface is a function of the blood flow in a given area. Surface blood flow has not been extensively related to basic physiological parameters, but there is some indication that it may relate to emotional reactions. Absorption of light in the visible range may also be useful in this measurement.

Breathing sounds have been readily detected with standard communications equipment, to the point of being a problem in aircraft communications. Directional microphones should be able to pick up respiratory sounds at some distance and provide respiratory rate data.

Eye movement and eyeblink have been used by some as a measure of arousal. There are problems in correlating these parameters, but there is good probability that eyeblink and motion can be detected remotely.

The above parameters are summarized in Table 3 for comparison. It must be emphasized that the feasibility of these measures have been established on the basis of a literature survey with limited preliminary data. Of primary importance in establishing the ability to use such methods for monitoring and/or obtaining experimental data are their statistical relationship to primary physiological variables.

The next phase of a study of remote monitoring techniques should establish the correlation between the suggested techniques and parameters measured by currently accepted direct techniques. All seven methods should be studied intensively.

Table 3. Candidate Systems Summary (Areas for Immediate Study)

Physiological Measurement / Parameter	Sensitivity	Accuracy	Reliability	Physiological Reaction	Candidate Technique
Volume displacement and normal surface movement / pulse rate, respiration rate, vibrocardiogram, respiration pattern	Chest wall motions of as little as 0.0001 inch can be detected by ultrasound and capacitance distance meters	Depends on amount of filtering required to remove breathing, etc.; estimate 80% accuracy in reproducing chest-wall motions without breathing	Depends on S/N; high respiratory rate will decrease sensitivity to heart motion	None	Distance meter; ultrasound; RF absorption
Mass acceleration / pulse rate, Ballistocardiogram, gross body motion	Weightless ballistocardiogram range approximately 0.4×10^{-3}g to 5.3×10^{-3}g	Depends on coupling to chair	Depends on gross body-motion noise; measurement limited to periods of inactivity in chair or cot	None	Accelerometers on chair or cot
Electromagnetic (IR) radiation / skin temperature	Temperature ±0.1 F	±0.5 F	Depends on movement, vascular dilation, sweat and ambient temp.	None	IR thermometer
Electromagnetic (IR) absorption-radiation / skin temperature, surface vascularity	Skin at 33.5 C in a 20 C room will rise about 0.1 C in 5 seconds from exposure to 33.5 C radiant body	Depends on energy transfer to body and speed of response of IR thermometer	Depends on fixation of head	Slight warming	Pulse heat small area of forehead with flash bulb, diathermy, etc.; plot decay time as function of dilation, core temperature, drugs, etc.
Surface motion / EEG level	Eye blink within 45° of dead ahead; iris diameter within 10° of dead ahead; true sensitivity unknown	Eye blink, good (estimate); iris diameter, unknown	Unknown, probably good	Mild awareness to none	Coaxial source and detector as per opthalmoscope
Electromagnetic reflection / pulse rate, hemoglobin level	Unknown; depends on S/N levels	Unknown	Depends on ability to resolve reflected energy in ambient light	None	Absorp. of green light by hemoglobin in forehead
Sounds / breathing rate	Unknown; depends on S/N levels	Fair to good	Depends on S/N; depends on location of microphone	None	Directional microphone; helmet mounted communications

REMOTE MEASUREMENT OF EYEBLINK AND EYE MEASUREMENT

By mutual agreement (NAA and NASA-ERC), a decision was made to further survey the literature relative to eyeblink, eye movement, and arousal states. It was also decided to test the laboratory feasibility of measuring eye motions by a remote system. The remainder of this report is concerned with this effort.

The state of arousal or attentiveness seems to be the nearest approach to an objective measurement of motivation. Using the electroencephalograph (EEG) and evoked responses (photic stimulation) as a measure of arousal, it has been shown that the evoked response in the cat is greatly reduced when attentiveness is increased by the presence of a mouse (Reference 24). Similar studies on gross human EEG's and behavioral responses have led to a general and somewhat subjective correlation (Reference 25). Table 4 lists these correlations.

From a remote-monitoring point of view, the question must be asked: "What externally manifested response accurately reflects attentiveness or the arousal state?" After a cursory survey of body systems, the eye appears to be the organ of choice. Indeed, since the brain function is that which is to be monitored and since the eye develops embryonically from the same areas as the brain, it may be said that, from an anatomical point of view, the eye is a direct window to the brain.

Darwin (Reference 26) observed that the emotion of surprise was accompanied by a "raising of the eyebrow and a widening of the eyelids while displeasure (or unpleasant stimuli) elicited a narrowing of the eyelids and a lowering of the eyebrows. Pain, weeping, vomiting, etc., are accompanied by a tight closing of the eyelids, and in some cases may result in compression of the eyeball." Darwin does not list a continuum of eyelid responses between obvious extreme emotional situations; however, a varying degree of response with the intensity of stimulus may be postulated.

Other eye responses, such as motion (both voluntary and involuntary) and pupil size, have been studied in relation to emotion and/or arousal. Pupil responses have been reviewed recently (Reference 23). Evidence to date indicates that there is a continuum of responses of pupil size between extreme dilation during interesting or pleasing stimuli and extreme constriction during unpleasant or distasteful stimuli.

Table 4. General Correlations Between EEG and Arousal

Behavioral Continuum	Electroencephalogram	State of Awareness	Behavioral Efficiency
Strong, excited emotion; fear, range, anxiety	Desynchronized; low to moderate amplitude; fast mixed frequencies	Restricted awareness; divided attention; diffuse, hazy; 'confusion'	Poor: lack of control, freezing up, disorganized
Alert attentiveness	Partially synchronized; mainly fast low-amplitude waves	Selective attention, but may vary or shift; 'concentration;' anticipation; 'set'	Good: efficient, selective, quick reactions; organized for serial responses
Relaxed wakefulness	Synchronized; optimal alpha rhythm	Attention wanders - not forced; favors free association	Good: routine reactions and creative thought
Drowsiness	Reduced alpha and occasional low-amplitude slow waves	Borderline partial awareness; imagery and reverie; 'dreamlike' states	Poor: uncoordinated, sporadic, lacking sequential timing
Light sleep	Spindle bursts and slow waves (larger); loss of alphas	Markedly reduced consciousness (loss of consciousness); dream state	Absent
Deep sleep	Large and very slow waves (synchrony but on slow-time bases); random irregular pattern	Complete loss of awareness (no memory for stimulation or for dreams)	Absent
Coma	Isoelectric to irregular large slow waves	Complete loss of consciousness; little or no response to stimulation; amnesia	Absent
Death	Isoelectric; gradual and permanent disappearance of all electrical activity	Complete loss of awareness as death ensues	Absent

Studies using the electro-oculogram (EOG) have shown that eye movement and blink rate following visual tasks tend to vary with the duration and type of eye exercise during the task and may provide an objective measurement of fatigue (Reference 27).

The literature dealing with eye movement and particularly eyeblink and arousal state is particularly scarce. However, from anatomical, neurological, and physiological inferences it seems plausible to assume that some relationship exists. Current bench-model instrumentation is capable of monitoring eye movement and blink rate remotely and, if correlations can be established, a useful monitoring system may be developed.

PHYSIOLOGICAL ASPECTS

The general correlations between the EEG and arousal are listed in Table 4. In Lindsley's recent review, the importance of the reticular formation in the lower brain stem in regulating arousal states is emphasized. The so-called ascending reticular activating system (ARAS), when stimulated electrically, elicits behavioral responses associated with generalized alertness. The EEG patterns during stimulation of this system are identical to those seen in arousal—i. e., a shift from slow spindle bursts of sleep or alpha waves of relaxed wakefulness to a pattern of low-voltage fast waves referred to as activation.

The influence of the ARAS is apparently nonspecific and serves only to alert the cortex through the diffuse thalamic projection system (DTPS). The DTPS seems to regulate cortical activity and excitability and enhance recruitment in cortical neurons.

Wakefulness, in general, can be said to be a function of excitation of the reticular formation through the ARAS as a result of sensory inputs, corticifugal impulses originating in the cerebral cortex, or by humoral factors in the blood, especially those affecting the reticular formation. Since wakefulness and alertness are a function of ARAS activity at the cortical level and eye reflexes are of interest, some of the reflexes having cortical centers, or whose centers may be modified by cortical action, should be examined.

Pupillary reflexes are confined to constriction and dilation. Basically, the innervation of the cellary muscle controlling pupil diameter is through the sympathetic and parasympathetic division of the autonomic nervous system. The sympathetic branch innervates the dilator muscles, while the parasympathetic branch innervates the constrictor muscles. The light reflex of the pupil is probably mediated at the hypothalomic level, but stimulation of Motor Area 8 (precentral gyrus) of the cortex also elicits pupillary responses. The pathways and mechanisms behind this latter response are unknown; however, this response may be linked to the pupillary changes with emotion and attitude described by Hess (Reference 23).

There are also cortical centers involved in controlling movements of the eyelids. These areas are closely related to those controlling movement of the eyes—i. e., Area 8. Destruction of this area results in ptosis or drooping eyelids. There is evidence to suggest that a center for eyelid movement also exists in the occipital lobe closely related to centers associated with ocular movement (Reference 28).

The motor nerves of the eyelids are the facial nerve (seventh cranial) and the oculomotor (third cranial). These nerves have their ganglia in the brain stem, with connections to the thalamus and cortex via the medial longitudinal fasiculus.

Thus, it can be said that the anatomical relationships between the pupil, oculomotor muscles, and eyelids exist through their motor innervation. This is not to say that a functional relationship exists, because there are few or no data to justify such a conclusion. At present, it is postulated that a functional relationship between eyeblink, pupil diameter, and eye movement does exist. Also, these parameters related to the arousal state of the individual.

The preliminary studies, outlined in the following sections, will use attached and unattached sensors to provide initial data on these hypotheses.

EYE MOVEMENTS

The movement of the eyes may be voluntary and involuntary. In both cases, the movements are produced by the interactions of the standard set of six oculorotatory muscles to each eye. The four recti and two obliques are found in all vertebrates from fish to man, and in most species—certainly in man—they are by far the most rapidly acting muscles in the body. The two eyes move together in both involuntary and voluntary movements. For changes in fixation, they move in the same sense or direction in obedience to Donder's and Fisting's laws governing the interaction of their muscles; but they move in opposite senses, toward or away from each other, for changes in accommodation. These contradictory tendencies are controlled from separate centers but are smoothly blended without conflict whenever we turn our gaze to a new object lying both in a new direction and at a new distance. Voluntary eye movements can be said to be those made for exploratory purposes, while involuntary movements can have their origin in many kinds of receptors in diverse sites. Some are included in the following discussion.

Many eye movements are associated with and initiated by activities of the vestibular system. If the head is fixed in relation to the body and the eyes are blindfolded or otherwise prevented from fixing on some aspect of the environment and the subject rotated in the horizontal plane, a relatively slow movement of the eyes may be observed in a direction opposite that of the movement (at the speed of the rotation) and fast flick back in the direction of rotation. If rotation is continued at a constant speed (no acceleration) or if the labyrinth is removed or the vestibular nuclei destroyed, eye movements cease. The cause of the movements is thereby demonstrated to be an acceleratory stimulus to the semicircular canals. Such systemic movements may be produced by any other stimulus to the intact vestibular system (alcohol, caloric, electrical, etc.) or by unilateral destruction of a labyrinth or vestibular nucleus. The movements persist after section of the brain at the level of the oculomotor nucleus, showing that no cortical involvement is necessary; only the midbrain is involved.

Tilting or rotating the head in the frontal plane (about a saggital axis) will produce a counter-rolling of the eyes in man and in other animals with forward-directed eyes. In like manner, tilting the head about a bi-temporal axis will produce similar eye movements in animals with laterally directed eyes. In all animals after movement is over, the eye catches up with the head in all but a small amount (about 1/10) of the rotation. Controlled experiments have shown that the source of these movements resides in the labyrinth but that the movements are due to a stimulation of the otolith rather than the semicircular canals. The cortex is also not required for counter-rolling; in fact, decerebration appears to significantly enhance the process.

Bending the neck in man and other animals produces conpensatory eye movements. These movements persist when fixation is prevented and are diminished but not abolished by labyrinthine destruction. Small compensatory movements have been demonstrated in man when the head is kept still and the trunk is moved. The origin of these reflexes has been shown to be muscle spindles in the muscles and joints of the neck.

If the head is fixed but the visual field is moved, the eyes will follow over a certain range. This following or pursuit movement is interrupted by a quick flick of the eyes in the opposite direction and the pursuit movement recommences. Optokinetic nystagmus is thus produced. Although both vestibular and optokinetic nystagmus produce the same ocular effects, their neural pathways are different. Destruction of the vestibular nuclei will not abolish optokinetic nystagmus but ablation of the visual cortex will prevent its occurrence.

Besides optokinetic movements, the eye responds to other visually induced reflexes directed primarily toward obtaining and retaining fixation of a visual target. When fixation has occurred, the eye has been shown to undergo small drifts, flicks, and movements, all causing the image to shift from spot to spot on the fovea. It has been demonstrated that when the image remains in a constant position on the fovea, adaptation occurs and the image fades. The fixation movements of the eye, then, prevent adaptation of the cones by continually shifting the image from one to another.

Other reflex movements termed saccadic movements occur during pursuit of a moving visual target or in frequent shifts from one target to another, as in reading. The amplitude of these movements is generally fixed and cannot be changed voluntarily, and the periodicity tends to adapt itself to that which is most efficient for the situation. The described movements are necessary for vision because, if the sensory fibers in the visual pathway are left intact but the motor fibers in the occipito-collicular tract (a part of the reflex pathway) are cut, a form of cortical blindness will result since the eye cannot now hold the visual image.

The pathways for the various reflexes involving eye movement are generally fairly well defined. In man, any reflex involving retinal stimulation as the initiator requires the transmission of the image to the visual cortex in the occipital lobe, and a lesion anywhere in the normal visual pathway (retina, optic nerve, optic tract, lateral geniculate body, visual cortex) up to and including the visual cortex will abolish the reflex. The efferent or motor pathway is comprised of occipito-collicular fibers that carry impulses from the visual cortex to the tectum or superior colliculus, rightly called the reflex center for ocular motility, and thence to the appropriate nuclei of the motor nerves governing eye movement, the oculomotor, trochlear, and abducens. If the efferent impulses originate in structures other than the retina—e.g., vestibular system, neck muscles, cerebellum, areas of the cortex other than visual, etc. —the visual cortex is not a necessary inclusion and the basic reflex arc involves no structures higher than the superior colliculus. As might be guessed from the richness of its associations, the superior colliculus is not only a motor reflex center but apparently functions as the center for all conjugate movements of the eyes.

EYEBLINK

Eyeblink may be defined as a gentle, rapid closure of the eyelids. The rate of blinking varies, but each blink occupies about 1/40 of a second. In the human blink, the upper eyelid travels the greater distance, 75 to 80 percent of the total distance between the upper and lower lids. The movement of the lids is accompanied by a slight upward rotation of the eyeball so that the palpebral aperture corresponds to the extreme lower margin of the cornea, with the upper lid covering the entire cornea. The eyeblink may be voluntary; it may be the result of an irritating stimulus to the eyelid, conjunctiva, and cornea; it may result from the retinal stimulation of an object approaching the eye; or it may occur rhythmically and be of unknown origin.

Musculature

The main muscle involved in eyelid movements is the orbicularis occuli. The orbicularis is a sheet of concentric muscle fibers covering the lids and the regions of the forehead and face around the orbital margin. This muscle may be divided into the orbital and the palpebral parts.

The orbital part comes into play on forcible closure of the lids; its contraction is accompanied by a general shift of the lids toward the center and by the formation of many folds in the overlying skin.

The palpebral portion of the orbicularis functions alone in gentle closure of the lids, as in blinking or sleeping. Its action is largely involuntary. This muscle forms two half-elipses, one on each lid. It may, in turn, be divided into a preseptal part and a pretorsal part, the details of which are of no concern here. The upper and lower preseptal portions are, however, the main depressor of the upper lid and the main elevator of the lower lid, respectively.

Innervation

The motor fibers to the orbicularis occuli are derived from the temporal branches of VII, the facial nerve. The branching occurs as the nerve passes through the parotid gland. The major branches are the temporal, cervical, and zygomatic. The lid also receives some motor fibers from III, the oculomotor nerve, but these terminate in the elevator muscles of the lid and play only a minor role in the eyeblink.

The sensory fibers supplying the lids are derived from the ophthalmic (first) and maxillary (second) divisions of V, the trigaminal nerve. The upper lid and the medial and lateral extremities of both lids are supplied by the ophthalmic division, while the central part of the lower lid is supplied by the maxillary division.

Eyeblink Control

As mentioned earlier, eyeblink can be voluntary or reflex. The cortical area implicated in voluntary control is located in the middle of the frontal cortex, Area 8 of Brodmann, closely associated with the centers for eye movement. In addition to this area, certain parts of the occipital (visual) cortex will produce lid movements when stimulated. This region is, however, thought to be more related to visually mediated reflexes rather than voluntary control per se. The center of integration between these cortical areas as well as the exact pathways over which the impulses travel are unknown. Additional relationships with the motor cortex and with lower visual centers of the brainstem have been predicated but never demonstrated experimentally.

Reflex closure of the eye in eyeblink—when initiated by a visual stimulus, an object approaching the eye, or a bright light—appears to involve the visual cortex (occipital lobe). The impulses pass from the retina to the visual cortex with apparently some involvement of midbrain centers on ascent (probably in the tectum). The return pathway apparently has synaptic connections in the superior colliculus before going to the motor nucleus of VII, the facial nerve, probably by way of the medial longitudinal fasciculus. This reflex is generally referred to as the optic reflex.

When eyeblink is initiated by a mechanical stimulus, it is termed the wink or sensory reflex. This reflex seems to be entirely subcortical, involving the trigeminal fibers and sensory nucleus of the trigeminal nerve in the afferent pathway, possibly including some mesencephalic center and thence through the bulbospinal nucleus of VII, and outward through facial fibers in the efferent path.

The periodic blinking of the lids is ordinarily involuntary and unconscious. Its chief value seems to be in moistening and cleaning the cornea. One might, therefore, expect the drying of the cornea to initiate the blinking reflex, but numerous experiments have shown that this is not the case. Though many factors have been tested for their effect or lack of effect on the acceleration or inhibition of the rhythmical blinking of the lids, the immediate cause of it remains unknown.

RELATIONSHIP BETWEEN OCULAR VARIABLES AND EEG

It may be noted from the foregoing material that, both from anatomical interconnections and physiological associations, there exists a rich potential for changes in pupil size, blink patterns, and variations in eye movements to occur concomittantly with changes in the electroencephalogram. The occipital and frontal cortices, the midbrain, and the hypothalamus are some of the more important structures implicated in the various reflex and involuntary activities of the eye. These same centers have been shown to exert major influences over EEG patterns. Hess (Reference 29) stimulated extensively in the diencephalon of waking cats with chronically implanted electrodes and produced changes in pupil size in conjunction with changes in arterial pressure, respiration, and many other activities including electroencephalographic patterns. The center involved in reflex eye movements, the occipital cortex, is capable of giving eye movements in many directions when its different areas are stimulated (References 30 and 31). It is in this area that shifts from the alpha rhythm to desynchronization and back to alpha are initially observed in the EEG tracing when the subject opens and closes his eyes. The frontal cortex, thought to be the site of voluntary eye movement, exhibits the initial arousal pattern in the EEG during voluntary motor activities.

Extensive eye movements were produced by Hess (Reference 32) when the superior colliculus of the cat was stimulated; potential changes in this same area have been reported by Apter (Reference 33) during voluntary eye movements. This area corresponds to that reported by Moruzzi and Magoun (Reference 34) as the area where stimulation of the reticular core produces patterns of electroencephalographic arousal and by Magoun (Reference 35) as the area where lesions produce EEG sleep patterns. Other centers involved in the control of eye movement show similar overlap with the production of EEG changes; the previous relationships are cited as prominent examples.

Considering this anatomical and physiological foundation, it is surprising that more work has not been done in correlating ocular variables with electroencephalographic changes during ongoing activities in humans. The measurement of eye movements and blink rates by electro-oculographic techniques has had extensive treatment in the hands of Dr. Christine Kris, wherein the variables were studied during visual tracking and pursuit tasks, in determining visual field defects, in observing drug effects on normal eye movements, and correlated with fatigue and alertness. The amount of Dr. Kris' work devoted to direct correlation with EEG patterns is, however, not extensive (References 36 and 37).

In 1957, Dement and Kleitman (Reference 38) observed that a phase occurs during sleep when the normal high-voltage, low-frequency EEG sleep patterns shift to a low-voltage pattern much more similar to the normal waking pattern. This pattern shift is accompanied by a series of rapid eye movements, termed REM, which give the name to this sleep phase (REM period). If the subject is awakened during the REM period, he will, in 80 percent of the cases, report that he was dreaming, compared to only 7 percent during a period when no rapid eye movements were observed. Hodes (Reference 39) demonstrated a difference in threshold for stimulation in the cortex, vestibular system, and reticular formation during sleep and the REM period, leading him to believe that a different mechanism was at work during this period than during other phases in the sleep cycle.

A similar type of eye movement was observed by Lorens (Reference 40) in subjects during mental multiplication. Other physiological variables were measured but the only physiological correlation of statistical significance that could be made was with an increase in the percentage of alpha blocking (desynchronization) in the occipital EEG pattern.

Jacobson (Reference 41) performed additional studies on physiological correlates of mental activities and found that some eye movement correlated with visual imagination and recollection. A closer correlation was observed, however, with neck muscle tension. It is of interest that there is a direct relationship, as noted earlier, between tension in the neck muscle spindles and eye position and movement.

Two studies of correlation between eyelid movement and EEG pattern might be noted. Kennard (Reference 42) noted that, during ongoing mental activity accompanied by EEG desynchronization, a blink would produce a return of the alpha rhythm, which would continue for several seconds after the blink. The duration of the postblink alpha rhythm seemed to bear some correlation with the performance of the subject on the mental task; a poor performance induced by fatigue appeared to be accompanied by an increase in the postblink alpha rhythm duration. These findings were said to be preliminary. Kajiwara (Reference 43) noted that a negative blocking of the alpha rhythm (continuation of the alpha rhythm rather than desynchronization), when the eyes were opened during EEG recording, appeared in some subjects with mental disease as well as in normal subjects on the borderline of sleep but still able to obey the command to open the eyes.

Most of the work cited is of interest and suggests fruitful areas for further investigation, but it does not represent a definitive correlation between the EEG and ocular variables. Two reasons might be suggested for this lack. First, in most of the investigations only one variable—pupil size, eyeblink, or eye movement—was studied, while it may be that a combination will present the best correlation. Second, it is well known that the EEG is recalcitrant to change. Considering the scope and variety of the mental states in the waking animal, a measurement essentially limited to two alternatives, alpha rhythm or disynchronization, is not a very sensitive descriptor. Eye movements unrelated to EEG changes seem to have been the more sensitive indicator of performance and fatigue, and further investigation may reveal their additional superiority as a status indicator.

PRELIMINARY INSTRUMENTATION SETUP

The concept of measurement of eyeblink, eye movement, and possible pupil diameter without attached sensors depends entirely on the measurement of reflected light from some portion of the eye. If the light path is directly along the longitudinal axis of the eye, retinal reflections may be obtained; other angles give reflections from the iris and/or the sclera.

In a recent paper (Reference 44), Alpern et al. compared the spectral transmittance of visible light by the retina of eyes with the cornea removed to that of enucleated eyes with the cornea intact. In general, the reflectance of the sclera is constant throughout the visible range. The maximum reflections for the retina, on the other hand, are above 600 mμ.

If visible light reflectance is to be used in an operational sense, the background interference from normal illumination must be considered. A 50 foot-lambert illumination level was selected for this purpose. Figure 1 shows the fundamentals of the system used. Obviously, this light source (ambient and experimental) produced pupillary constriction and the signal-to-noise ratio was less than desirable.

A near-infrared system was set up (Figure 2). The basic advantage of the near-infrared wavelengths is that they allow much higher energy levels to be utilized without discomfort to the subject.

Illumination was supplied for the experiment by a microscope illuminator using an incandescent ribbon-filament lamp. The visible light was removed with a Wratten infrared filter and the resulting transmitted light focused on the subject's face by placing a small front surface mirror within the beam of the collimated illumination so that the light was directed away at an angle of 90 degrees from the source of illumination in front of the viewing optics. The light coming from the subject was passed through a second Wratten filter of the same transmission characteristics as the illuminating beam and then focused on the sensitive surface of the image-converter tube with suitable lens combinations. The viewing surface of the image-converter tube was observed with the aid of an eyepiece magnifier and was photographed with a 35mm camera for illustration in this report (Figure 3). As may be seen from the photographs, the retinal response (with the addition of the front surface specular reflection) is of a predominantly higher intensity than the illumination of the surrounding eyelid and face. The photographs were exposed on standard plus x film and developed to a speed of ASA 2000. The

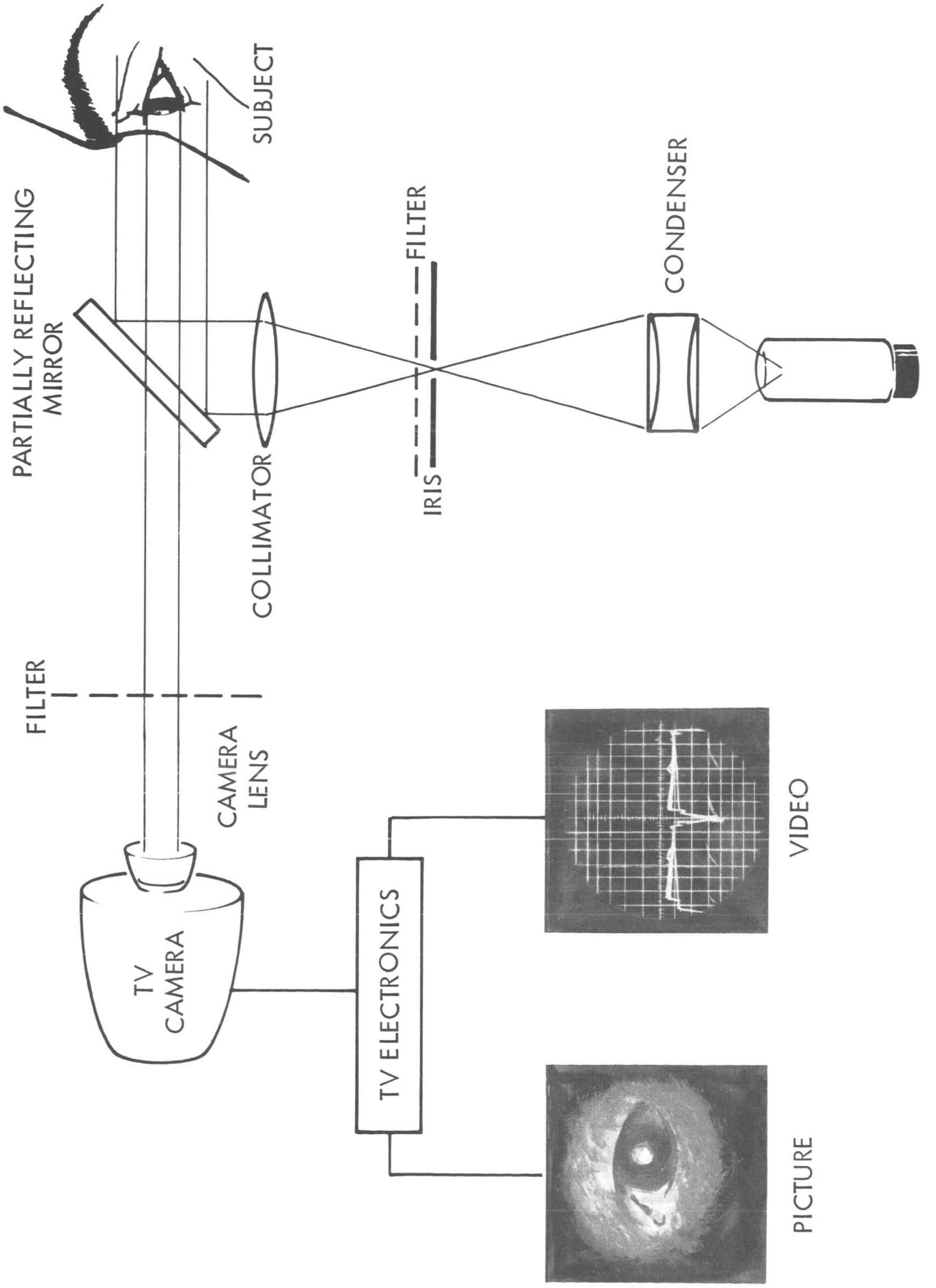

Figure 1. Schematic of TV Coaxial-Collimator Retinal Illuminator-Viewer

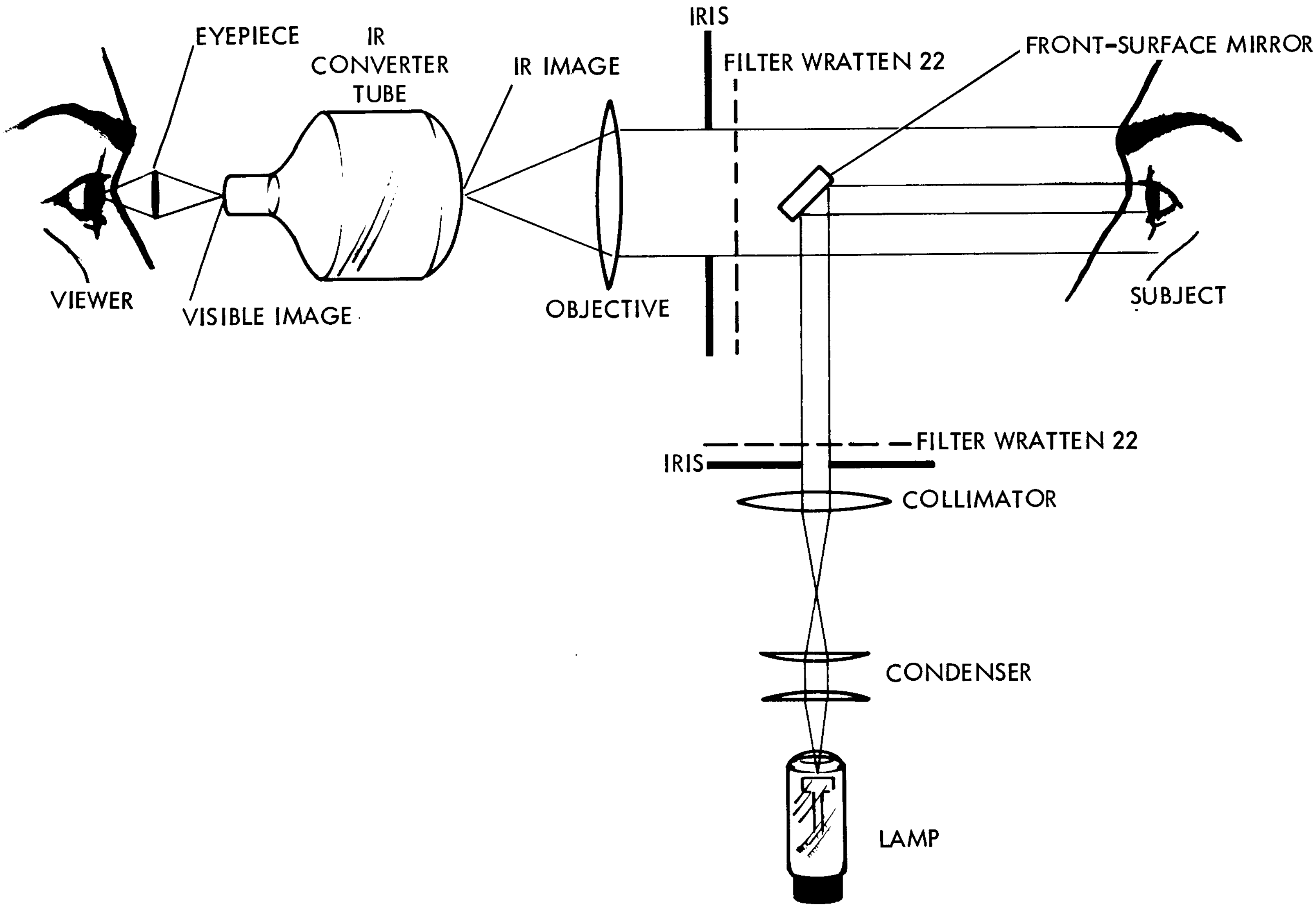

Figure 2. First Infrared Coaxial-Collimated Illuminator-Viewer Setup for Wide Field of View

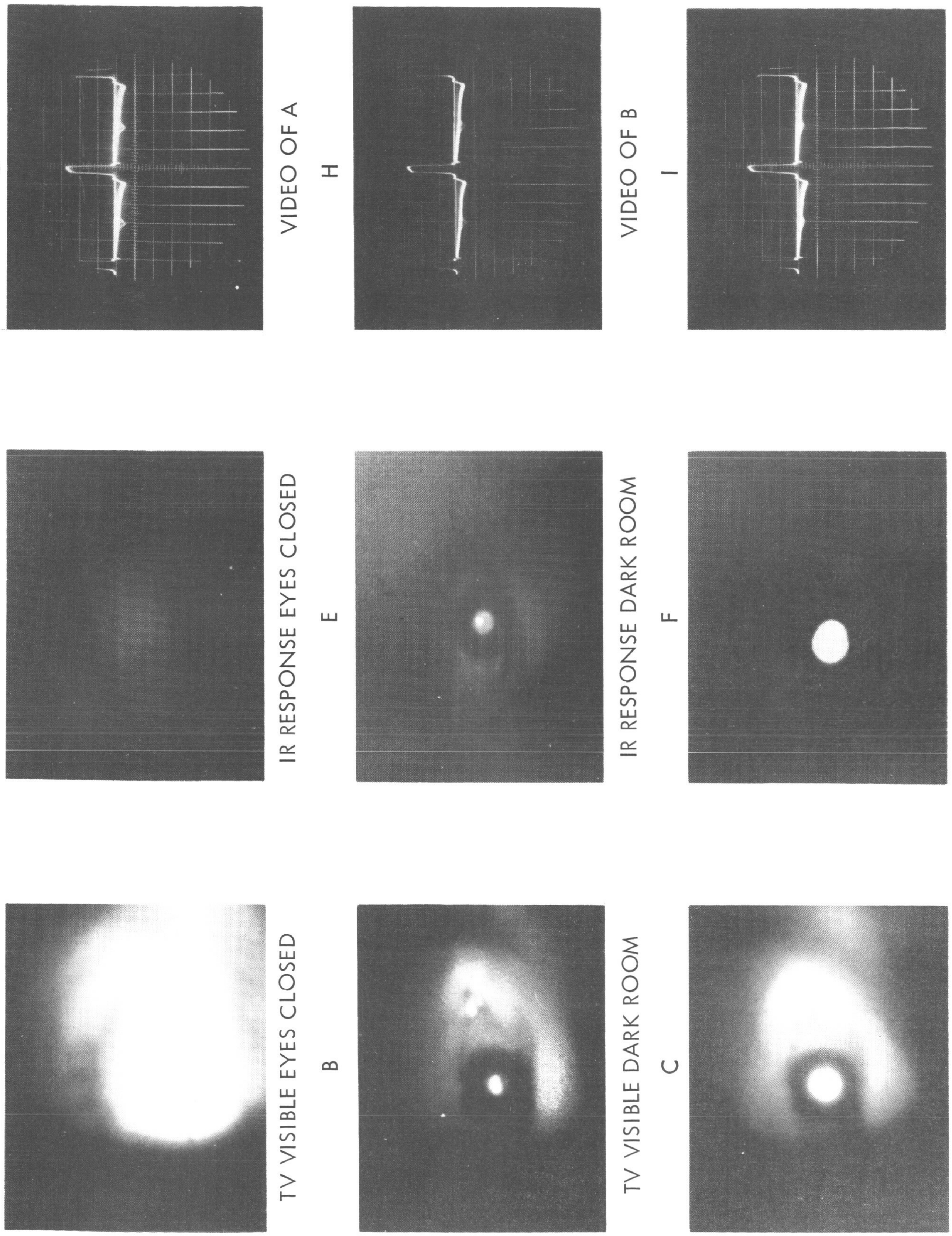

Figure 3. Viewing Surface of Image-Converter Tube Observed With Aid of Eyepiece Magnifier

printing does not afford the contrast that is evident and a result of the film grain. It does illustrate the feasibility of using this technique in a lighted room.

Since a practical system would include methods for intensifying the contrast obtained in the reflection, a television system was used in the visible region to illustrate methods of image enhancement by adjustment of the contrast and blanking controls. Operation in the visible region was found to require filtering of the illumination source to remove wavelengths not directly involved in the retinal reflection. This requirement is true predominantly in the yellow-green and blue regions of the spectrum, which tended only to cause excessive subject discomfort and eye-watering. Wavelengths in the orange and red regions tended to be tolerated readily by the subject and could be used for periods suitable for equipment adjustment. For an extended period, it will be necessary that the subject receive the lowest possible illumination levels, which can be achieved only in a semidarkened room.

The television/visible light technique was refined by combining the light source, the beam-splitting mirror, and the television camera on a tripod head that could be positioned in any direction. An available 500-watt projection lamp was used for the illumination source. No effort was made to use a collimating lens and, therefore, the light striking the subject's face is slightly divergent in nature. This is easily compensated for by the focusing adjustment of the television camera, and usable corneal responses are produced. This system also allowed experimentation with compensation for the distance of the subject's gaze from a fixed point, which influences the divergence or convergence of reflected light. It was found that small refocusing adjustments of the television camera can compensate for the distance between the subject and the point of his gaze.

The output from the image converter or TV scanner can be displayed on a CRT and, with suitable amplification, on an oscillograph. CRT photographs are included. Eye movement, eyeblink, and retinal reflectance are easily identified. The TV scanner used was a GPL series 151 and the output was displayed on a Cohu monitor model DRM-8 2R.

Of interest, but as yet only speculative, is the possibility of obtaining an indication of retinal temperature through its reflectance. The retinal reflectance obviously is related to its blood content and, in turn, the temperature should be related to the blood flow. It is known that cerebral blood is maintained fairly constant over a wide range of possible changing factors. Whether this is true in the eye or not is not fully known. (In positive or eyeballs-down accelerations, blood flow in the eyes is known to be altered significantly.)

EYE REFLECTIONS AND BACKGROUND REFLECTIONS

As noted previously, background lighting affects the sensitivity of eyeblink and eye movement measurement. Reflections from other soft tissues around the eye, such as the eyelid, are also important. It is obvious that the difference in reflection of visible or infrared light between the eyeball and the eyelids is the primary measurement of eyeblink, and that discrimination of iris reflection and sclera reflections in the presence of soft tissue reflections is the primary measurement of eye movement.

Using white light, it was observed that the intensity of reflection was greater from the soft tissues than from the eyeball. A spectrophotometric analysis was not performed, but it is assumed from the literature that eyelid, cornea (or iris), and scleral tissue would have maximum and minimum reflectance at different wavelengths. Selective filtering and/or beam-splitting techniques might be useful in enhancing the sensitivity of these measurements. A scanning TV camera provided sufficient discrimination to demonstrate feasibility.

Under low background illumination, it is possible to detect changes in pupillary diameter by measuring the transit time of the vidio sweep across the iris. Reflections from the front surface of the eyeball are adequate for this purpose. Direction and frequency of eye movements may also be detected with such a system. It was not possible at this time to refine our system because of the scan rate of the TV camera and the inherent drift of the vacuum tube system. Solid-state, high-scan-rate equipment would allow much more accurate measurements.

ILLUMINATION OF THE EYE

Several methods of illumination of the eye in the visible and near-infrared regions were attempted. Collimated light directed along the line of sight was much more preferable than were diffuse or point light sources. Two methods were tried in providing the necessary combining of the line of sight and illumination. One method was the use of a lightly silvered mirror in front of the television camera; this technique, while supplying sufficient illumination because of the large high intensities available, proved troublesome because of the secondary reflection of the transmitted light on the walls of the room bouncing back directly into the camera lens. A second method was the use of small, heavily silvered mirrors placed directly in the line of sight of the television camera; this technique proved much more successful. It was feasible because of the large diameter of the objective lens compared to the size of the mirror. A small portion of the light returning from the subject to the television camera was obscured by the mirror and sent back to the light source. This did not significantly deteriorate the picture quality and caused only a small loss in the total light available at the TV camera. This technique allowed illumination of the subject without any detectable interference from scattered illumination within the room.

OBSERVATION TECHNIQUES

In the observation of a subject's eyeball reflections, one major area of compromise must be rectified; this is the size of the subject response compared to the overall field of view that must allow for normal head motions. This can only be approximated at this time through what can be considered a normal situation. The 50mm focal length lens on the currently available television camera provides a field of view that is 8 by 12 inches wide when the camera is mounted 53 inches away from the subject. This has been found to be satisfactory for the type of program planned; however, longer focal length lenses can also be used satisfactorily in the laboratory environment, since it is often desirable to move the television camera farther away from the subject to reduce the amount of clutter in the area of the subject's visual task. During experimentation with the image-converter tube mounted on an optical bench, various focal length objective lenses were used; among these were a negative Barlow lens to extend the focal length. Generally speaking, it was found that, by using longer focal length objective lenses and placing the subject farther from the point of observation, there was less sensitivity to defocusing through positioning of the subject's head. The decrease in available illumination became a limiting factor at greater distances.

In using an image-converter tube, it is not possible to significantly alter the contrast of the object under observation.

CONCLUSIONS

The capability for remote measurement of eyeblink, eye movement, and pupillary diameter has been demonstrated. Refinement of the necessary instrumentation, signal conditioning equipment, and data analysis equipment seems well within the capability of present technology.

The correlation of eye motions and changes with arousal states and/or performance of higher mental tasks is a different matter. Literature surveyed in this study indicates that anatomical and physiological systems exist and that a theoretical correlation is possible; however, empirical evidence is not quite so strong. It is apparent that experiments to date have not had such a total correlation in mind, nor have they been conducted with blink, pupil response, and eye movements as independent variables.

Eye motions and changes seem to present a possible indicator of higher mental functions, and are certainly an area recommended for further research. The key problem in this area is in correlating the parameters of eyeblink, eye movement, and pupil diameter with the classical EEG arousal state and mental tasks. The correlational phase of such an effort need not employ an unattached sensor, but may rely on the EOG as a basis of measurement. The measurement of pupillary diameter will be more difficult but not impossible. Simple photographic data may be adequate.

If the required correlations are to be obtained, the following programs are recommended:

1. Establishment of standard measurement techniques for EOG and pupil diameter for future use; it is also necessary to establish criteria for arousal states, EEG analysis, and mental tasks to be performed.

2. Establishment of an intensive experimental program to determine the existence or nonexistence of correlations; this phase should include a large number of subjects undergoing a series of induced physiological changes selected for performance or arousal degradation.

3. If a significant correlation is found, the development of a remote monitoring system; some problems recognized at this time are spectral reflectance of eye and surrounding tissues, design criteria for optimum optical and scanning systems, and design criteria for a data acquisition system.

APPENDIX A. CHEST WAVEFORMS VIA NONCONTRACTING DISTANCE METER

The use of a capacitance distance meter (Wayne Kerr Co., Model DM-100) to measure thoracic and cardiac changes was accomplished. The sensor was mounted on a rigid (nonseismic) structure. The position of the sensor was adjusted so that it was approximately two inches above the point of maximum apical heartbeat (Figure A1).

The output of the distance meter contained both a high-frequency (above 1 cps) and a low-frequency (below 1 cps) component (trace 5, Figure A2). Separation of these components was accomplished by selective filtering through Krohn-Hite filters. The component between 0.1 and 1.5 cps was clearly a respiratory pattern. The component above 1 cps was a complex waveform but contained peaks corresponding to the R wave of the ECG.

It was reasoned that the high-frequency component was a measurement of the velocity imparted to the chest wall by heart action. As such, its first derivative should transform the wave into a measurement of acceleration of the chest wall. If these assumptions were correct, the derivative should correlate with the clinical vibrophonocardiogram, also an acceleration measurement. Traces 2 and 3 of Figure A2 show the correlation between these two measurements. Further analysis was not attempted at this time; however, the degree of visual correlation observed leads one to suspect that they are closely related.

Work is in progress under contract to the NASA Flight Test Center (Contract NAS2-923, Development of Vibrocardiographic Instrumentation) to develop and validate phonovibrocardiographic instrumentation. Results to date indicate that a correlation between this measure and cardiac output exists. Thus, there is a strong possibility that the distance meter may provide an unattached sensor for indirect measurement of cardiac output. Further study is required.

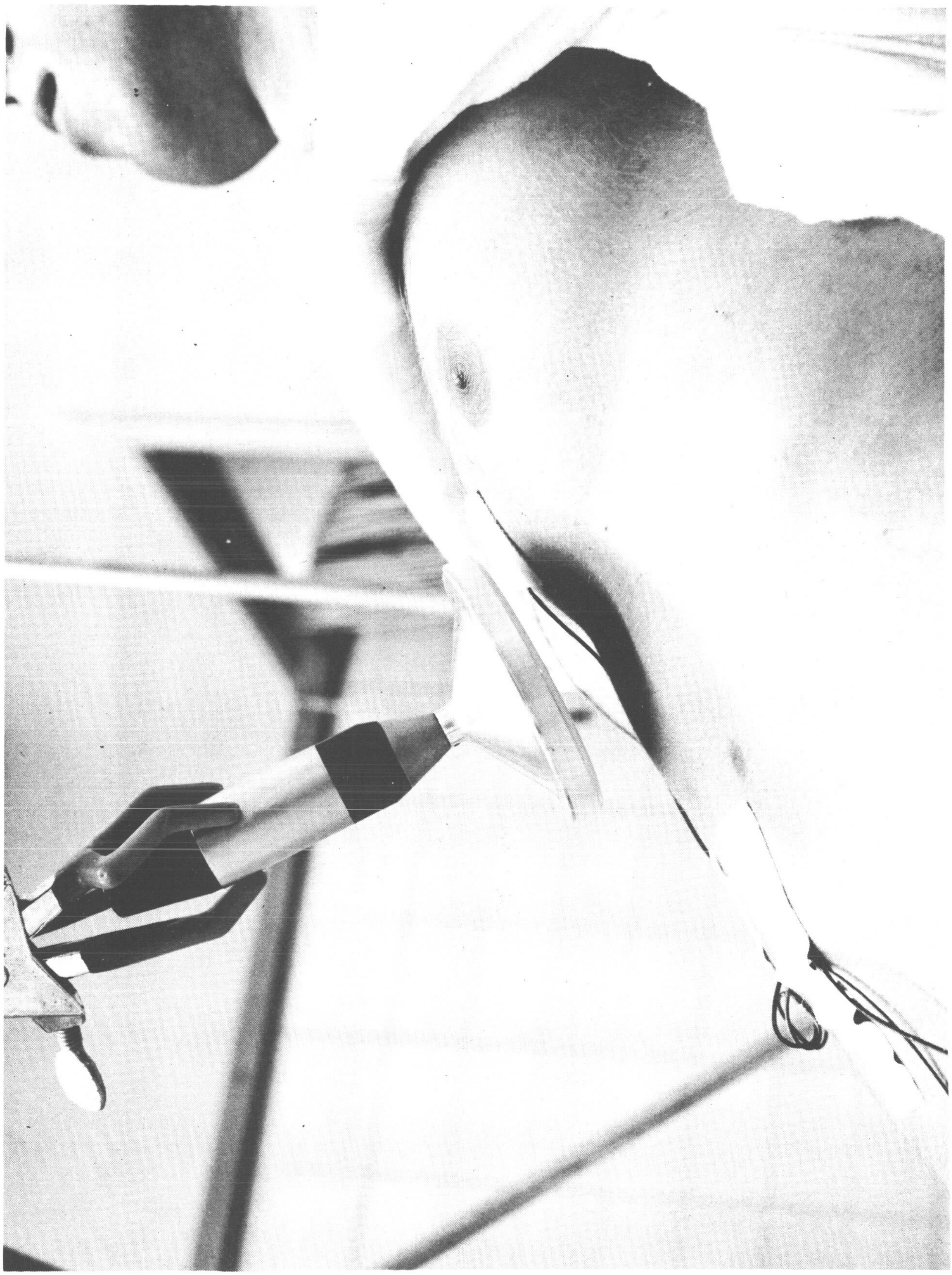

Figure A1. Sensor Positioned Two Inches Above Point of Maximum Apical Heartbeat

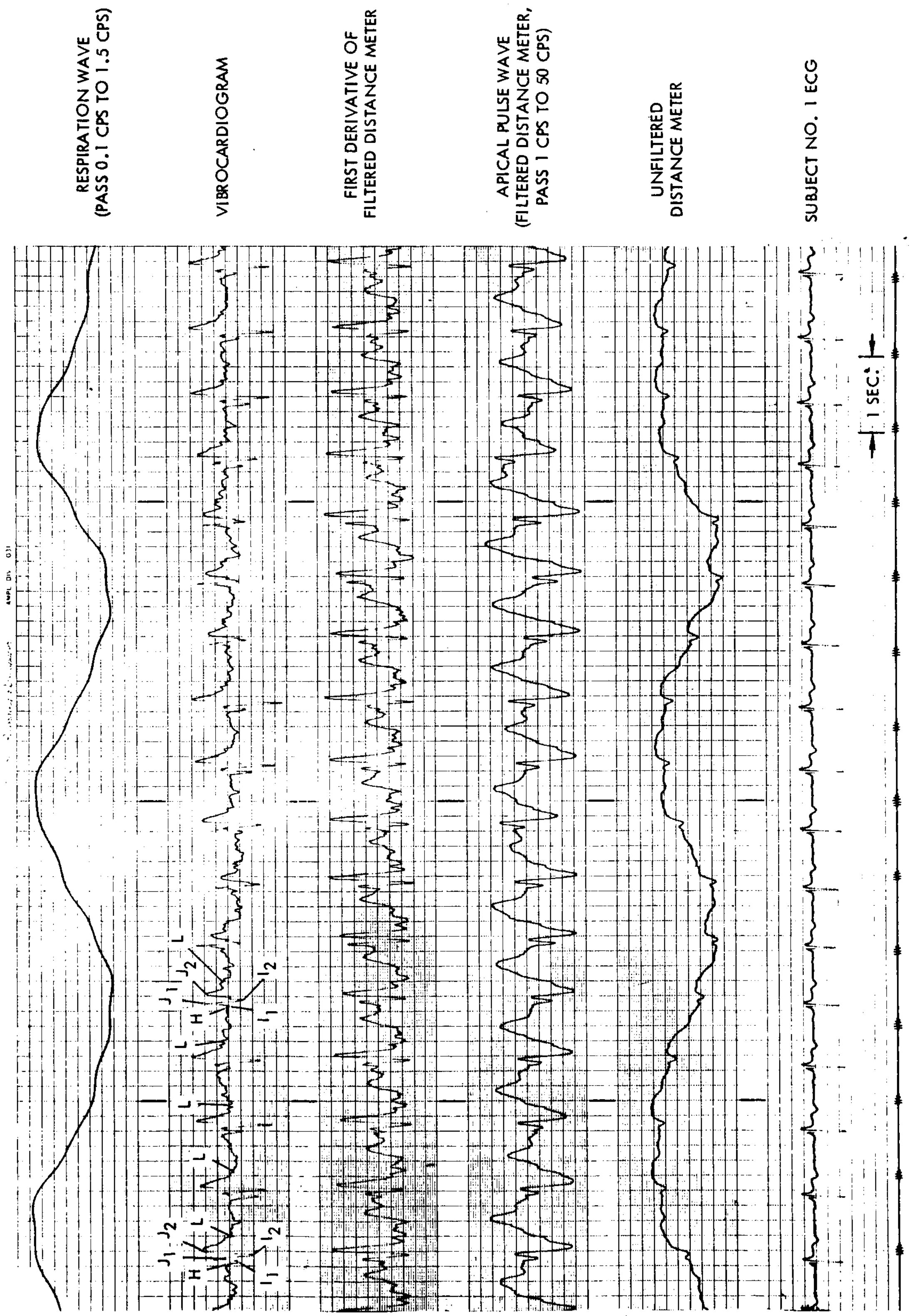

Figure A2. Patterns Obtained by Use of Capacitance Distance Meter

APPENDIX B. EEG MEASUREMENTS

The correlation of eye movement and eyeblink with EEG arousal states would require a knowledge of the relationship between EEG leads and EOG (electro-oculogram) leads. It is conceivable that the muscle action potential from the oculomotor muscles could mask the EEG because their amplitude is approximately an order of magnitude higher. In addition, it is desirable to identify which lead pair (e.g., frontal, paretial, occipital) could be used for best correlation.

Initially, the adjustable EEG monitoring headband (Figures B1 and B2) was used. This headband was developed on the Apollo program (NAS9-150) and the design submitted under the New Technology clause as Technology Utilization, TU No. SID 55381, April 1966. For comparison, standard needle electrodes were also used. No significant difference between the two methods was noted.

Figure B3 is an oscillogram of the EOG and paretial EEG during blinking and eye movement. Similar oscillograms were obtained with the frontal and occipital leads of the EEG. It would appear from these tracings that the muscle action potentials are indeed being transmitted to the EEG electrodes, blanking the EEG measurements.

Further measurements and analyses are needed to verify this hypothesis. There are, however, several techniques that might alleviate this problem and produce clinical-type EEG's. Among them are selective filters, different lead positions, etc. For correlative purposes, it might prove more reliable to use a different measure of arousal states.

Figure B1. Adjustable EEG Monitoring Headband in Use

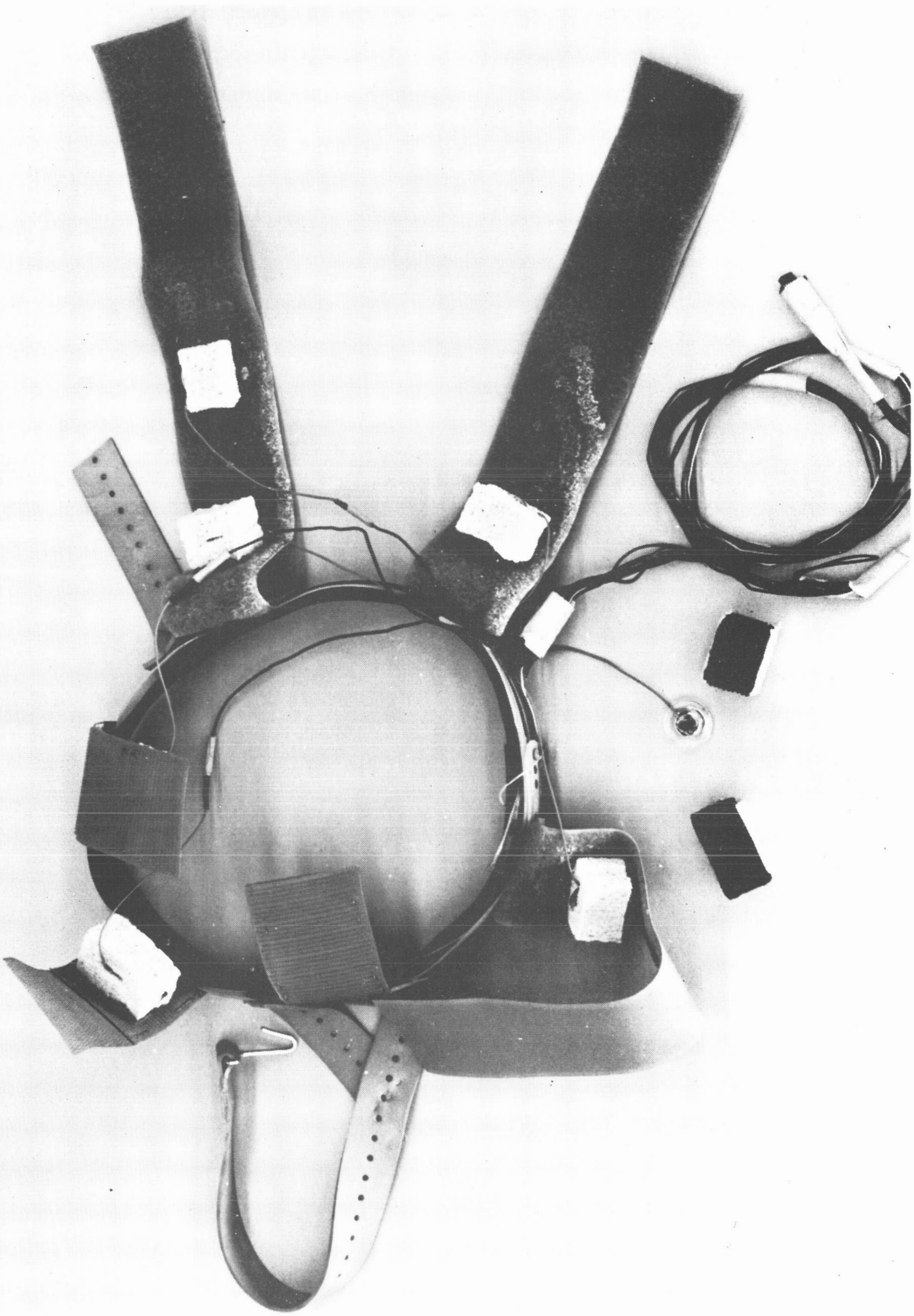

Figure B2. Components of EEG Monitoring Headband

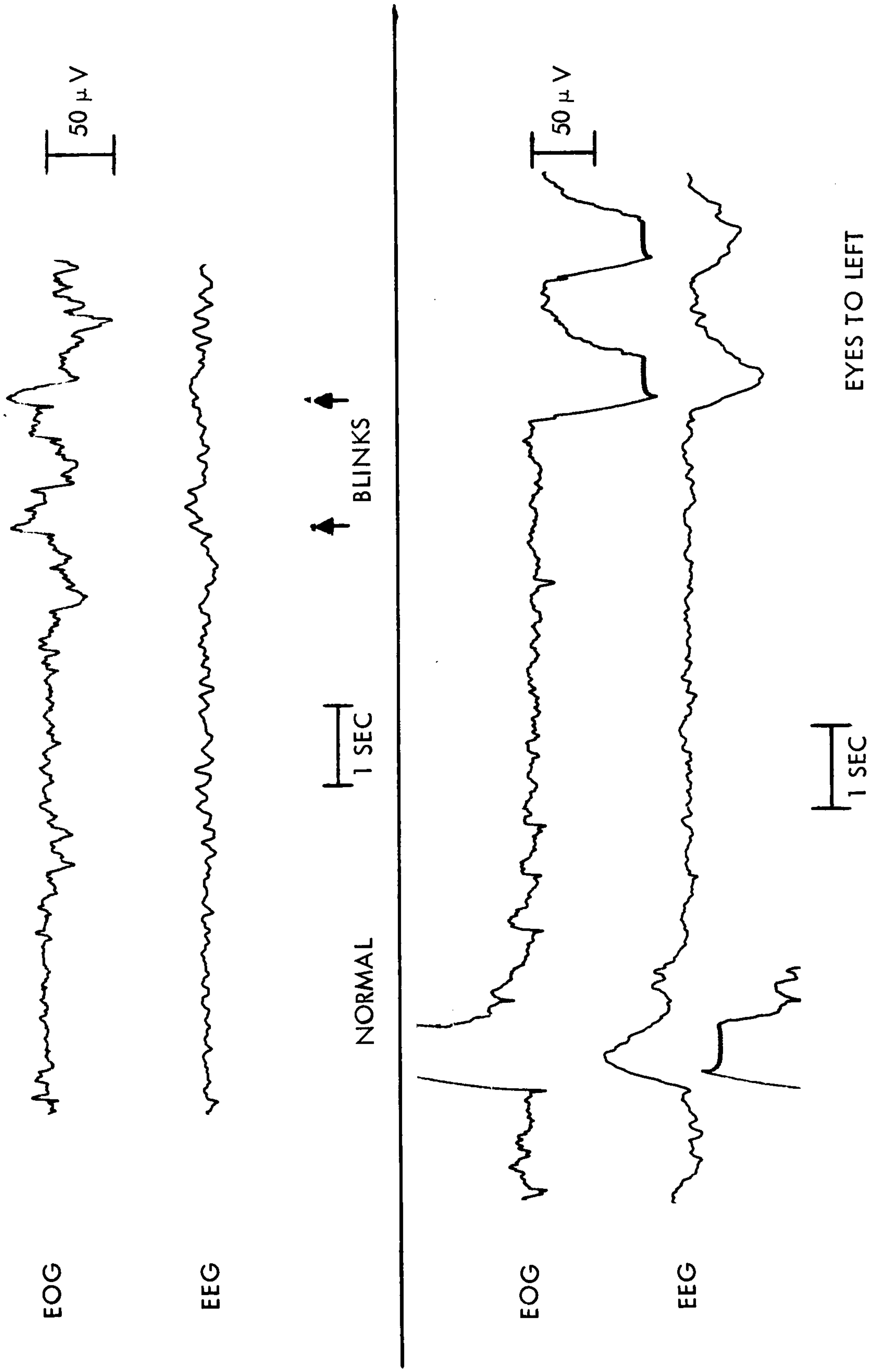

Figure B3. Effect of Eye Movement on Parietal EEG

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